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Ta-based interface ohmic contacts to AlGaN/GaN heterostructures

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Al/Ti based metallization is commonly used for ohmic contacts to *n*-GaN and related compounds. We have previously reported an ohmic contact scheme specially designed for AlGaN/GaN heterostructure field-effect transistors (HFETs) [D. Qiao *et al.*, Appl. Phys. Lett. **74**, 2652 (1999)]. This scheme, referred to as the ''advancing interface'' contact, takes advantage of the interfacial reactions between the metal layers and the AlGaN barrier layer in the HFET structure. These reactions consume a portion of the barrier, thus facilitating carrier tunneling from the source/drain regions to the channel region. The advancing interface approach has led to consistently low contact resistance on $Al_{0.25}Ga_{0.75}N$/GaN HFETs. There are two drawbacks of the Al/Ti based advancing interface scheme, (i) it requires a capping layer for the ohmic formation annealing since Ti is too reactive and is easily oxidized when annealing is performed in pure N_2 or even in forming gas, and (ii) the atomic number of Al and that of Ti are too low to yield efficient backscattered electron emission for *e*-beam lithographic alignment purposes. In this work, we investigated a Ta based advancing interface contact scheme for the HFET structures. We found that the presence of Ta in this ohmic scheme leads to (1) a specific contact resistivity as low as $5\times10^{-7}\ \Omega\,\text{cm}^2$, (2) efficient electron emission for *e*-beam lithographic alignment, and (3) elimination of the capping layer for the ohmic annealing. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1365431]

I. INTRODUCTION

AlGaN/GaN heterostructure field effect transistors (HFETs) are important devices for high power, high frequency, and high temperature applications. To achieve a high transconductance and a high saturation current, high quality ohmic contact with a contact resistance well below 1 Ω mm is essential.[1] Several metallization schemes, including Al/Ti, for ohmic contact on AlGaN/GaN HFETs, bulk GaN and AlGaN layers have been recently reported.[2–12] However, it is difficult to achieve low contact resistance on AlGaN due to that the Schottky barrier height of many metals on AlGaN is larger than 1 eV.[13] For the AlGaN/GaN heterostructure, a two-dimensional electron gas (2DEG) is induced at the AlGaN/GaN interface due to the piezoelectric effect and spontaneous polarization.[14–17] For such a heterostructure, an ohmic contact with low contact resistance can be obtained by thinning the AlGaN barrier in the source and drain regions, thus enhancing carrier tunneling across the energy barrier in these regions. This can be implemented by selective growth or by reducing a thick AlGaN layer using selective etching or solid phase reactions without affecting the gate area. The first two methods require multiple processing steps. The simplest way to reduce the barrier, however, is to use the ''advancing interface'' reactions.[8] In this approach, nitride forming metals, such as Ti and Ta, are used to form contacts in the source and drain regions. During subsequent annealing, the contact metals are expected to consume part of AlGaN barrier to form a conducting metallic phase (metal–nitride) thus resulting in a thinner barrier in contact with the metal–nitride layer [see Fig. 1(a)].

The Al/Ti/HFET metallization is the most commonly used ohmic contact on AlGaN/GaN HFET devices reported in the literature. For this metallization scheme, the metals react with the AlGaN layer to form a metallic $AlTi_2N$ layer with AlGaN. This reaction leads to a N-deficient AlGaN region, believed to be heavily *n*-doped, beneath the $AlTi_2N$ contact layer. However, the final barrier thickness depends strongly on the original thickness of the AlGaN layer and the annealing conditions. A commonly used Al/Ti/HFET contact consists of Al(710 Å)/Ti (300 Å). For this contact, all of the Al reacts with ~250 Å of Ti to form Al_3Ti at 250 °C to 300 °C, with the remaining Ti reacting with the AlGaN barrier. For samples with thick AlGaN layers (⩾300 Å), the conventional metallization does not consume enough AlGaN barrier layer to enhance carrier tunneling.[5] We have shown that a metallization scheme of Al(200 Å)/Ti(1500 Å)/HFET could lead to a greatly reduced contact resistance, due to a substantial consumption of AlGaN to form $AlTi_2N$.[8] This scheme is referred to as the advancing interface contact. For

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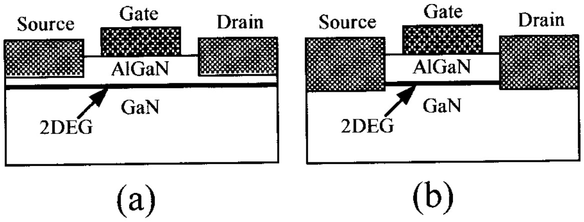

FIG. 1. Shown here are schematics of the advancing interface contacts after annealed at 950 °C, (a) the Ta-based advancing interface contact [Al(500 Å)/Ti(500 Å)/Ta(500 Å)/HFET, sample No. 3]. After reaction, a much thinner AlGaN layer remained. (b) the Ti-based advancing interface contact [Al(200 Å)/Ti(1500 Å)/HFET, sample No. 2]. After reaction, the entire AlGaN layer was consumed.

this metallization, Al and Ti react to form $AlTi_3$ (not Al_3Ti as in the conventional scheme) at 250 °C to 400 °C, leaving about 900 Å of Ti in excess to fully react with the AlGaN layer to form the $AlTi_2N$ phase. This reaction leaves little or no AlGaN layer in the HFET source and drain region, thus resulting in efficient tunneling and a much reduced specific contact resistivity, ρ_s.

While the advancing interface contact leads to improved contact resistance, there are drawbacks for this metallization; (i) the metallization requires a capping layer for the annealing to prevent surface oxidation, and (ii) the atomic number of Al and that of Ti are too low to yield efficient backscattered electron emission for the alignment marks to be clearly visible using *e*-beam lithography. It has been shown that Ta reacts with N to form a metallic phase TaN, similar to TiN.[18,19] Ta also has a higher atomic number (73) than Al (13) and Ti (22), and is expected to have much higher emission efficiency of backscattered electrons. For these reasons, we investigated the use of Ta-based reactions to form the advancing interface contacts.

II. EXPERIMENT

The structure of the AlGaN/GaN HFET used in this work consisted of n-$Al_{0.24}Ga_{0.76}N(250\,Å)/Al_{0.24}Ga_{0.76}N$ $(30\,Å,\text{undoped})/i$-$GaN(1\,\mu m)$/sapphire. The heterostructure was grown by metalorganic chemical vapor deposition. The method of transmission line measurements (TLM) was used to investigate the contact resistance. Three types of samples were fabricated. Sample No. 1 consisted of the conventional Al(710 Å)/Ti(300 Å)/HFET, sample No. 2 was the previously reported advancing interface Al(200 Å)/Ti(1500 Å)/HFET, and sample No. 3 was a Ta based contact with a layer structure of Al(500 Å)/Ti(500 Å)/Ta(500 Å)/HFET. Mesa isolation of the HFET samples was accomplished by photoresist patterning and reactive ion etching with CCl_2F_2 gas. This was followed by TLM patterning to achieve standard lift-off techniques for ohmic metal definition. Before metal deposition, all samples were etched in $HCl{:}HF{:}H_2O(1{:}1{:}2)$ solution for eight seconds before loading into an *e*-beam evaporation system equipped with dry pumps with a chamber base pressure of $\sim 10^{-8}$ and $\sim 10^{-7}$ Torr during metal deposition. After metal deposition and lift-off sample No. 2 was encapsulated with a sputtered AlN layer followed by annealing in a rapid thermal annealing furnace at 650 °C for 40 s, 850 °C for 40 s and then 950 °C for 5 min in a flowing forming gas ambient. After annealing, the AlN capping layer was removed in hot (80 °C) phosphoric acid. Sample Nos. 1 and 3 were annealed directly without caps at 650 °C for 40 s, 850 °C for 40 s and 950 °C in a flowing forming gas ambient. The annealing time at 950 °C was 40 s for sample No. 1 and 4 min for sample No. 3 to obtain the lowest contact resistivity. The samples were characterized using dc electrical measurements, cross sectional high-resolution transmission electron microscopy (HRTEM) and Rutherford backscattering spectrometry (RBS).

III. RESULTS AND DISCUSSION

Table I summarizes the contact metallization and dc electrical properties for the three samples. Sample No. 1 had the largest specific contact resistivity, $\rho_s((5.8\pm0.9)\times10^{-4}\,\Omega\,cm^2)$, followed by that of sample No. 2 $[(7\pm1)\times10^{-5}\,\Omega\,cm^2]$, and sample No. 3 yielded the lowest contact resistivity $[(5\pm2)\times10^{-7}\,\Omega\,cm^2]$. Inspection of the surface of sample Nos. 1 and 3 after annealing using scanning electron microscope and optical microscope indicated uniform and smooth surface morphology. This smooth surface was achieved without any capping layer during annealing. The surface morphology of sample No. 2 after annealing and the removal of AlN was also smooth. However, a capping layer was required during annealing to yield the smooth surface, in this particular ohmic processing scheme.

TABLE I. Contact resistance, sheet resistance, and contact resistivity of different metallization schemes on HFETs $(Al_{0.24}Ga_{0.76}N(250\,Å)/Al_{0.24}Ga_{0.76}N(30\,Å,\text{undoped})/i$-$GaN(1\,\mu m)$/sapphire). The annealing ambient was forming gas. Sample No. 2 was annealed sequentially at 650 °C for 40 s, 850 °C for 40 s, and 950 °C for 5 min with an AlN capping layer. After annealing, the AlN was removed in hot (80 °C) phosphoric acid. Sample No. 1 and No. 3 were annealed sequentially at 650 °C for 40 s, 850 °C for 40 s, and 950 °C without an AlN capping layer. The annealing time at 950 °C was 40 s for sample No. 1 and 4 min for sample No. 3. R_c is the contact resistance. ρ_s is the specific contact resistivity. $R_c=\sqrt{R_s\times\rho_s}$, R_s is the sheet resistance of the semiconductor. The reported values are the average value of at least 6 TLM lines. These results have been reproduced on HFET structures provided by two suppliers.

Sample number	Metallization scheme	R_c Ω mm	R_s Ω/□	ρ_s Ω cm^2
1	Al(710 Å)/Ti(300 Å)	5.6 ± 0.6	$(5.5\pm0.4)\times10^2$	$(5.8\pm0.9)\times10^{-4}$
2	Al(200 Å)/Ti(1500 Å)	2.1 ± 0.2	$(5.5\pm0.6)\times10^2$	$(7\pm1)\times10^{-5}$
3	Al(500 Å)/Ti(500 Å)/Ta(500 Å)	0.2 ± 0.1	$(6.1\pm0.3)\times10^2$	$(5\pm2)\times10^{-7}$

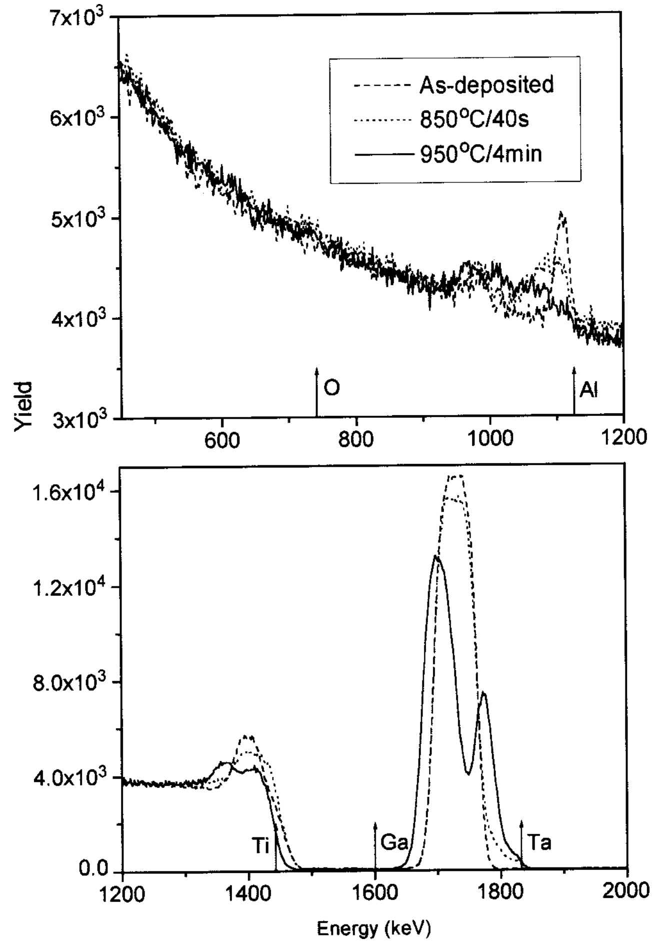

FIG. 2. RBS for the Ta-based contact before and after annealing in forming gas. The structure consisted of Al(500 Å)/Ti(500 Å)/Ta(500 Å)/AlGaN(280 Å)/GaN/ sapphire. The dashed line represents the sample before annealing, the dotted line for the sample annealed at 850 °C for 40 s and the solid line for the sample annealed at 950 °C for 4 min. The arrows indicate the surface energy positions of the elements. The scattering angle was 160 ° and the angle between the sample normal and the analyzing beam (He^{++} at 2 MeV) was 3°.

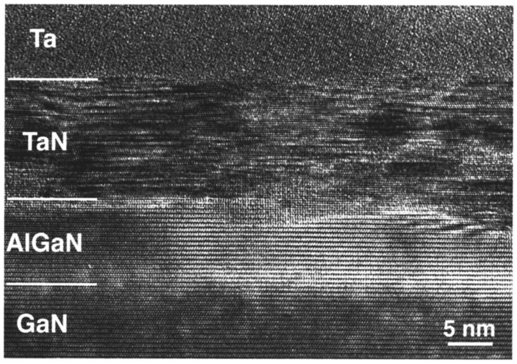

FIG. 3. Cross sectional HRTEM image of Al(500 Å)/Ti(500 Å)/Ta(500 Å)/HFET. The sample was annealed at 950 °C in forming gas for 4 min.

Figure 2 shows the RBS spectra of sample No. 3 (Ta-based contact) annealed at 850 °C and 950 °C. It was found that after annealing at 850 °C for 40 s, only reactions between metals (Al–Ti and Ti–Ta) were observed. After annealing at 950 °C for 4 min, however, there were extensive reactions between the remaining Ta and AlGaN. The back edge of the Ta signal extended to lower energies compared to that of the as-deposited sample, which suggests that Ta has reacted with AlGaN. Computer simulations of the RBS spectrum showed that about 150 Å of AlGaN was consumed in the reaction. It should be noted that the Ta signal centered at around 1730 keV split into two parts (solid line in Fig. 2, lower portion). This splitting was caused by the reactions between Ti and Ta. It can be seen that the Ti signal in the same spectrum has a similar shape. The dip in the Ta signal, implying a low Ta fraction, corresponds in depth to the bump in the Ti signal centered at 1365 keV, implying a high Ti fraction. This suggests that the composition of the Ti–Ta alloy is not uniform in depth. Figure 3 shows the cross sectional HRTEM image of an annealed Al(500 Å)/Ti(500 Å)/Ta(500 Å) sample, similar to that shown in Fig. 2, after annealing at 950 °C for 4 min. It can be seen that Ta has reacted with AlGaN to form TaN during annealing, reducing the AlGaN barrier layer thickness to about 100 Å. In some areas, only ~50 Å of AlGaN remained. This observation confirmed that the Ta-based metallization is an advancing interface ohmic contact.

The contact resistivity of the Ta-based advancing interface contact (sample No. 3) was three orders of magnitude lower than that of the conventional Al/Ti contact (sample No. 1) and about two orders of magnitude lower than that of the advancing interface Al/Ti contact (sample No. 2). The large difference in contact resistivity between sample No. 1 and sample Nos. 2 and 3 is expected since sample Nos. 2 and 3 had the advancing interface structures. The difference between sample Nos. 2 and 3 can be rationalized by the metal–AlGaN reactions. For the Ti-based advancing interface contact (sample No. 2), about 900 Å of Ti was available to react with about 280 Å of AlGaN after the low temperature formation of $AlTi_3$. The entire AlGaN was consumed in the reaction with the Ti layer after the high temperature annealing at 950 °C for 5 min. The reaction product $AlTi_2N$ was in contact directly with the undoped GaN without a barrier in between. The absence of the AlGaN barrier layer removes the 2DEG induced by the polarization effects underneath the metal contact. Contact is made between the 2DEG underneath the gate and the side of the metal contact [see Figure 1(b)]. This contact area is very small, thus causing high contact resistance. For the Ta-based contact (sample No. 3), only a thin AlGaN layer remained after the reactions (see Fig. 3), thus the 2DEG is expected to remain underneath the ohmic contact. Figure 4 shows the sheet charge as a function of the AlGaN barrier thickness calculated by the one-dimensional Poisson equation. It indicates that the sheet charge is still in the order of $10^{12}\,\mathrm{cm}^{-2}$ when the AlGaN barrier is about 50 Å in thickness. Therefore, the contact area between the contacts and the 2DEG is deemed to be much larger than that of sample No. 2. The final contact structure of this sample consists of $AlTa_xN$ (metallic)/AlGaN ($\leqslant$100 Å)/2DEG. This structure provides a high density of 2DEG with a much reduced AlGaN barrier layer thickness, resulting in low contact resistance values [see Figure 1(a)]. With the annealing procedure used in this work, the designed thickness of the AlGaN layer after reaction should not be less than 100 Å due to

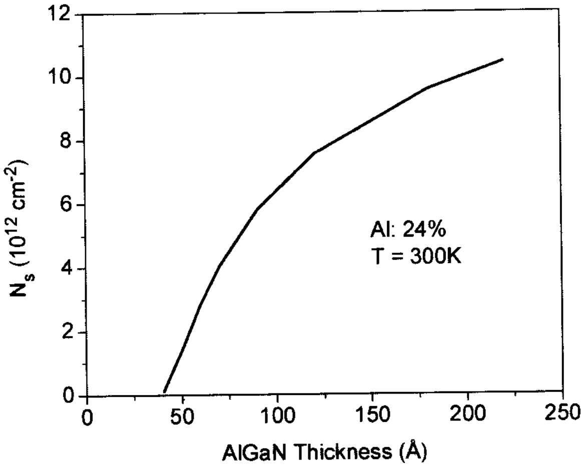

FIG. 4. Sheet charge density N_s as a function of AlGaN barrier thickness calculated by the one-dimensional Poisson equation. The Al fraction and the temperature were assumed to be 24% and 300 K, respectively, in the calculation.

the reaction front nonuniformity between Ta and AlGaN (see Fig. 3).

We have confirmed this interpretation of the difference between the contact resistances of sample Nos. 2 and 3 by varying the Ta layer thickness of the Al/Ti/Ta contact. The contact resistance decreased as the Ta layer thickness increased, until the Ta layer was too thick and consumed the entire layer of AlGaN. When this happened, the contact resistance increased after annealing (results are not shown here). There is thus an optimum thickness for the Ta based advancing interface contact.

The backscattered electron image of all three samples was examined. We found that the Ta-based contact (sample No. 3) gives much brighter images of contact pads as compared to those of sample Nos. 1 and 2. This observation demonstrates that *e*-beam lithographic alignment marks will indeed be much more clearly visible using the Ta-based advancing interface contact.

IV. SUMMARY

Ta-based advancing interface ohmic contacts on HFETs provide the following advantages: (i) eliminate the necessity of an encapsulating layer during annealing, (ii) improve the yield of the backscattered electron emission for more accurate alignment in the *e*-beam lithographic process, and (iii) allow for a controlled reaction between Ta and the AlGaN layer to reduce the barrier thickness without eliminating the 2DEG. A properly designed and fabricated Ta-based advancing interface contact system is deemed more suitable for HFET applications than the Ti-based contact system.

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